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**Final Report:  
Sediment Flux and Trapping on the Skagit Tidal Flats  
N00014-08-1-0163**

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## **LONG-TERM GOALS**

The long-term objective is to determine the hydrodynamic processes controlling sediment transport and the associated morphologic response on tidal flats.

## **OBJECTIVES**

The objectives of our research program were:

- quantify the influence of barotropic (tidal) convergence on the lower Skagit tidal flats as a mechanism of sediment trapping and creation of ephemeral mud and sand deposits;
- determine the role of density fronts in creating and transporting high-concentration sediment suspensions, and assess the influence of these processes on sediment deposition and short-term morphological change;
- distinguish the influence of wave-induced sediment transport from tidal/fluvial processes, and determine how variations in tidal, fluvial and wind/wave forcing alter the bedform geometry, transport pathways, surficial sediment characteristics and tide-flat morphology .

## **APPROACH**

We deployed an array of instrument platforms on the Skagit Bay tidal flats and the lower Skagit River (Fig. 1) during a one-month observation period in June, 2009. The measurements on the flats were conducted with instrumented frames that included pulse-coherent acoustic velocity profilers, acoustic Doppler velocimeters (ADV), acoustic backscatter sensors (ABS), optical backscatter sensors (OBS), temperature-salinity sensors (Seacat and RBR), and vertical profiling acoustic velocity sensors (ADCPs) (Fig. 2). During this period we also performed high-resolution surveys of the currents and suspended sediment distributions. An acoustic velocity profiler (Aquadopp) provided measurements at the mouth of one of the distributaries. Pressure sensors were deployed at various locations in the other distributaries.

## **WORK COMPLETED**

The moored array was successfully deployed and recovered in June, 2009. Surveys were conducted in early June and late June. The data were processed and analyzed, and preliminary results were presented at the ONR-sponsored meeting of the Skagit Bay DRI in October, 2009. Results were also presented at the Ocean Sciences meeting in February, 2010.

## RESULTS

### *Timeseries Observations*

During June 2009, the river discharge ranged from its year-to-date maximum of  $930 \text{ m}^3 \text{ s}^{-1}$  in early June to about  $450 \text{ m}^3 \text{ s}^{-1}$  by the end of the month (Fig. 3). The observation period spanned two spring tides and a neap, with stronger spring tides occurring around the solstice. Intense stratification was observed on the tidal flats, due to the large freshwater inflow (Fig 3 2<sup>nd</sup> panel). During neap tides, stratification remained strong for most of each tidal cycle, with surface-to-bottom differences of  $\sim 25$  psu. As tidal amplitudes and velocities increased, stratification decreased. Tidal currents ranged from 0.4 to 1.2 m/s. Stratification augmented the near-surface currents. Maximum currents were observed during the spring-tide ebbs at the end of the deployment. These conditions resulted in the strongest stresses, exceeding 2 Pa (Fig. 3 bottom panel).

The high stresses during these spring-tide ebbs also resulted in the highest suspended sediment concentrations and sediment fluxes observed during the study (Fig. 4). The integrated flux of sediment was found to be dominated by the contributions of the four ebb tides during this spring-tide period. Analysis of the dynamics of this regime indicates that once the water level drops below a critical depth (between 0.3 and 1 m, depending on the river outflow), the slope of the free surface approximates the slope of the flat, producing intense outflows, high stress, and strong seaward sediment flux.

The linked tidal variation in stratification, shear, and suspended sediment concentration was also apparent in the small-boat surveys of the tidal flats. Cross-flat surveys during spring tides found that after lower low tide the salinity gradient advancing across the flats during the flood was vertically well-mixed. Stratification began to develop on the upper flats around high water, and remained strong through the early part of the strong ebb. An example of the cross-flat distribution of salinity, velocity, and acoustic backscatter during a strong ebb is shown (Fig. 5). During transect 1 early in the ebb, the stratified region extended across most of the tidal flats. Velocities were highly sheared near the surface due to the stratification and river outflow, with currents of about  $0.5 \text{ m s}^{-1}$  in the surface layer and near zero in the lower layer. About 1 hour later, the stratification had broken down on the upper flats but remained on the lower flats; correspondingly, the backscatter signal was strong where the water column was well mixed. The transition point during this survey occurred near station 2, and the instruments there showed a similar transition from strong stratification and low sediment concentrations to well-mixed with high suspended sediment. By transect 3, the well-mixed, high-backscatter region extended to the edge of the flats.

### *Suspended sediment dynamics and stratified turbulence*

The data collected on Skagit tidal flats offers a unique opportunity to examine the effects of salinity stratification on suspended sediment dynamics in a macrotidal environment.



The multi-frequency pulse coherent Doppler measurements (Fig. 6) provide centimeter vertical resolution profiles of both mean flow and turbulence (via the 6 Hz sampling rate vertical velocity measurements from a downward aimed center transducer). These measurements are unique because the multi-frequency processing allows us to overcome the traditional range velocity ambiguities typically associated with pulse coherent Doppler profilers and still measure 1.3 m long profiles with mean velocities of  $\pm 1$  m/s. The Acoustic Backscatter Profilers (Fig. 7) provide high quality backscatter measurements also with cm vertical resolution and the widely spaced frequencies (1.0 , 2.5 and 5.0 mHz) combined with Optical Backscattering Sensors at 4 locations in the water column will help differentiate scattering from turbulent microstructure, fine sediment and sand resuspension. Nortek Vector ADVs at two heights will allow point measurements of turbulent velocity spectra, and thus serve as a consistency check for the pulse coherent Doppler turbulence measurements. Salinity measurements are also available at 2 to 4 locations in the water column depending on the site location.

The ABS backscatter (Fig. 7, left lower panel) shows strong scattering from an interface located at 40 cm above the bed (cmab), which was confirmed to be a salinity gradient with salinity sensors (not shown). The difference in the height of the interface is due to the ABS burst was taken 20 min before the PC-Doppler data. Bursts taken at the same time show the same interface height. Interestingly, the fresh water above the interface has much higher backscatter levels due to either turbulence microstructure or fine suspended sediment. OBS data will be used to examine this further. The turbulence measurements (RMS vertical velocity profiles, Fig. 5 upper right panel) from the pulse coherent Dopplers during ebb show a near bed peak in turbulence, followed by suppressed turbulence at the interface 20 cmab and then increased turbulence in the upper layer. During slack tide the vertical velocity fluctuations are dominated by short period waves, with the expected rapid decay in vertical velocity. During flood tide the vertical velocity measurements show a much uniform structure, and the along channel flow has a logarithmic profile consistent with the absence of stratification as measured by the salinity sensors.

During the spring tide at the beginning of the deployment with strong river outflow the ABS measurements often show high backscatter in the upper water column associated with the fresh water (Fig. 7, left panels). Salinity stratification maintains a low-turbidity lower layer through the end of the ebb and into the flood tide when mixing results in more vertically uniform properties. During the spring tide towards the end of the deployment, more energetic conditions were present due to large tides and larger waves. During an ebb tide in this period, the opposite situation from the previously shown ebb occurs, as stratification caps puffs of sand resuspension from mixing above 10 cm into the water column.

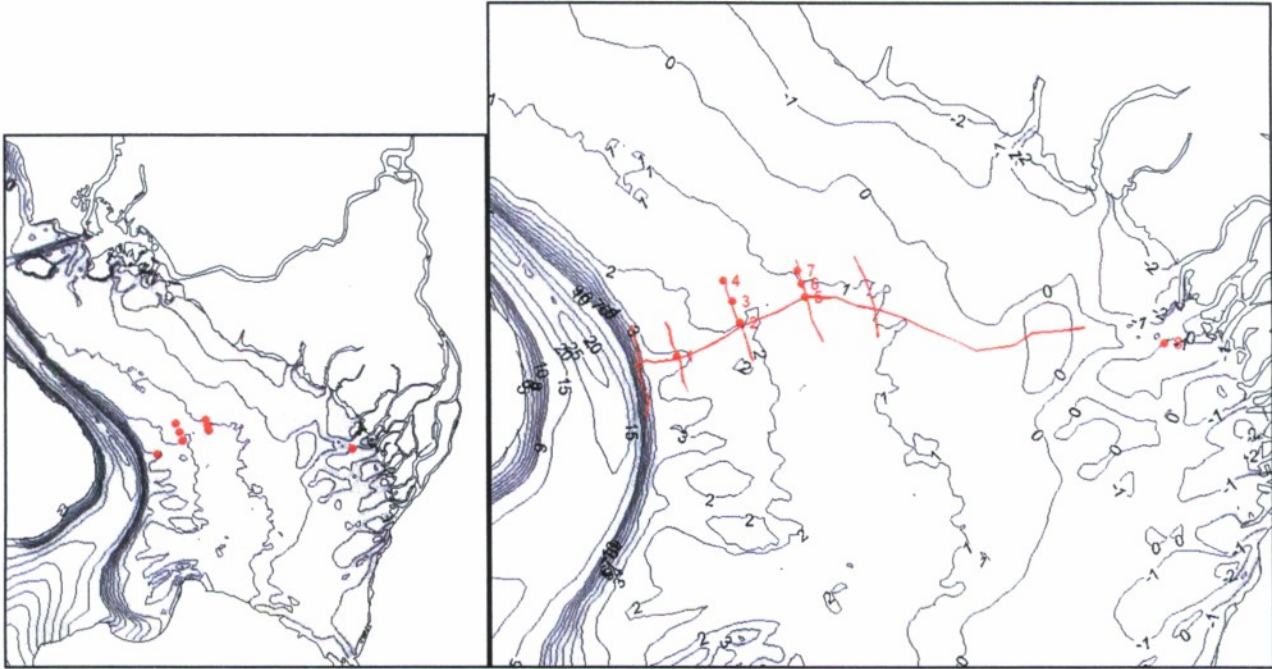
These measurements allow us to examine the details of the interaction of stratified turbulence and vertical profiles of sediment concentration as the stratification approaches the seafloor. These results will have applications to many other environments with stratified turbulence and sediment resuspension, such as estuaries or river outflows into open shelf environments.

## **IMPACT/APPLICATIONS**

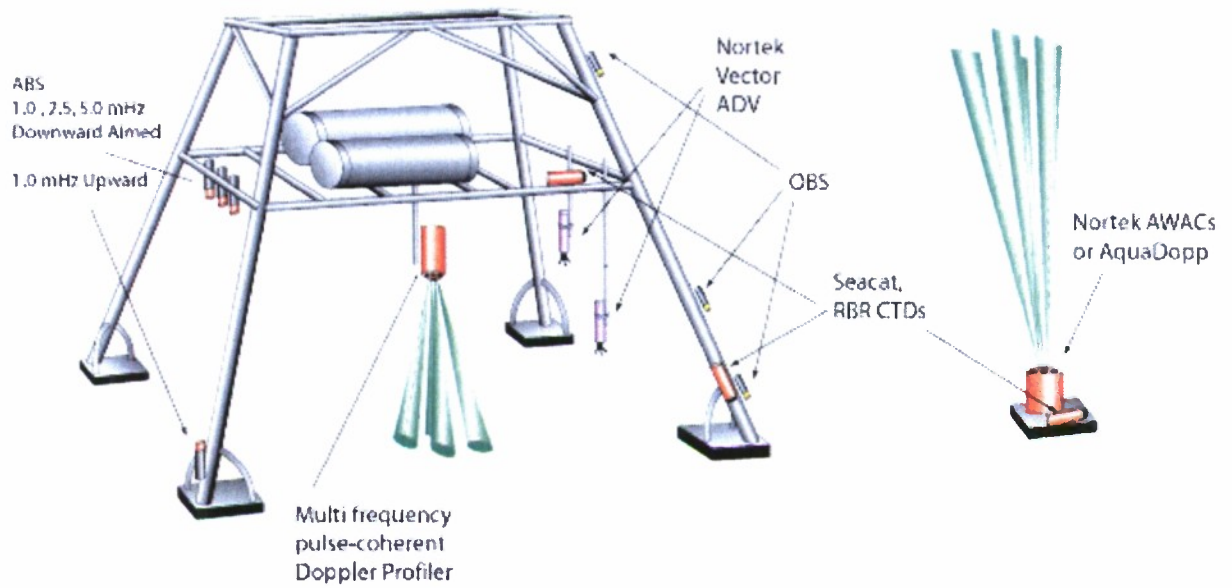
This project will contribute both to the understanding of and the ability to measure key physical variables in shallow coastal environments of interest to the Navy. Our particular ability to resolve the vertical structure of the flow and water properties has important implications for the application of remote sensing to these environments—the conditions at the surface may not be relevant to the conditions at depth, even in water depths of 1-2 m. The project also provides essential ground-truth for the development of morphodynamic models, which the Navy will use in the future to forecast changes in bottom morphology and sediment rheology. From the DURIP funding we are able to purchase new equipment allowing the measurement described to be conducted and allowing similar measurements in the future. In particular, the development of the multi-frequency pulse coherent Doppler will allow high resolution profiling even in extremely energetic conditions (flows  $> 1$  m/s), which was not possible with previous technologies.

## **RELATED PROJECTS**

Ralston is PI on a closely related project entitled “Sediment transport at density fronts in shallow water”, which involves modeling of the Skagit Flats using FVCOM. The analysis of these data is continuing in a project entitled “Sediment Flux and Trapping on the Skagit Tidal Flats: Analysis and Modeling”.

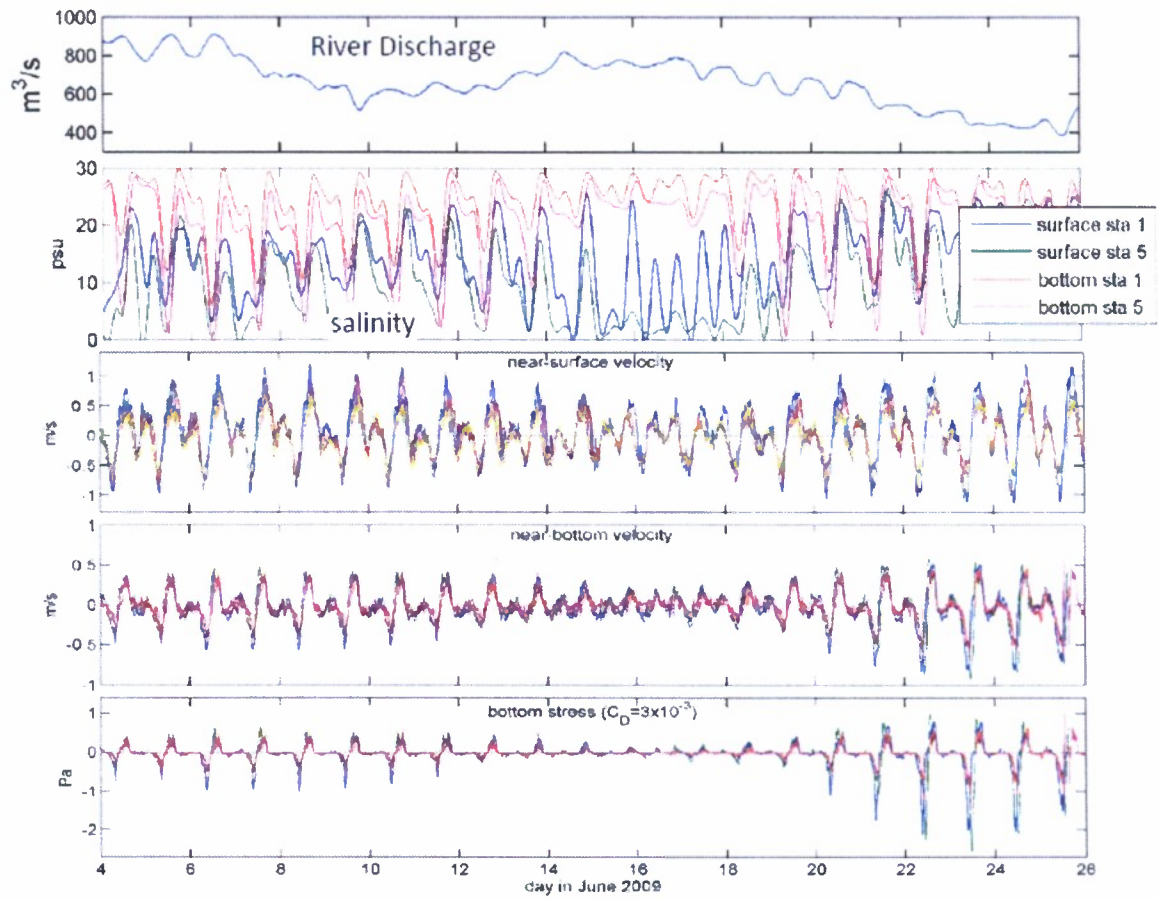


**Figure 1.** Bathymetry of the Skagit Bay tidal flats (left) with a zoom on the study area on the southern flats (right). Red dots indicate frame locations, and lines show across-flats and across-channel survey lines.

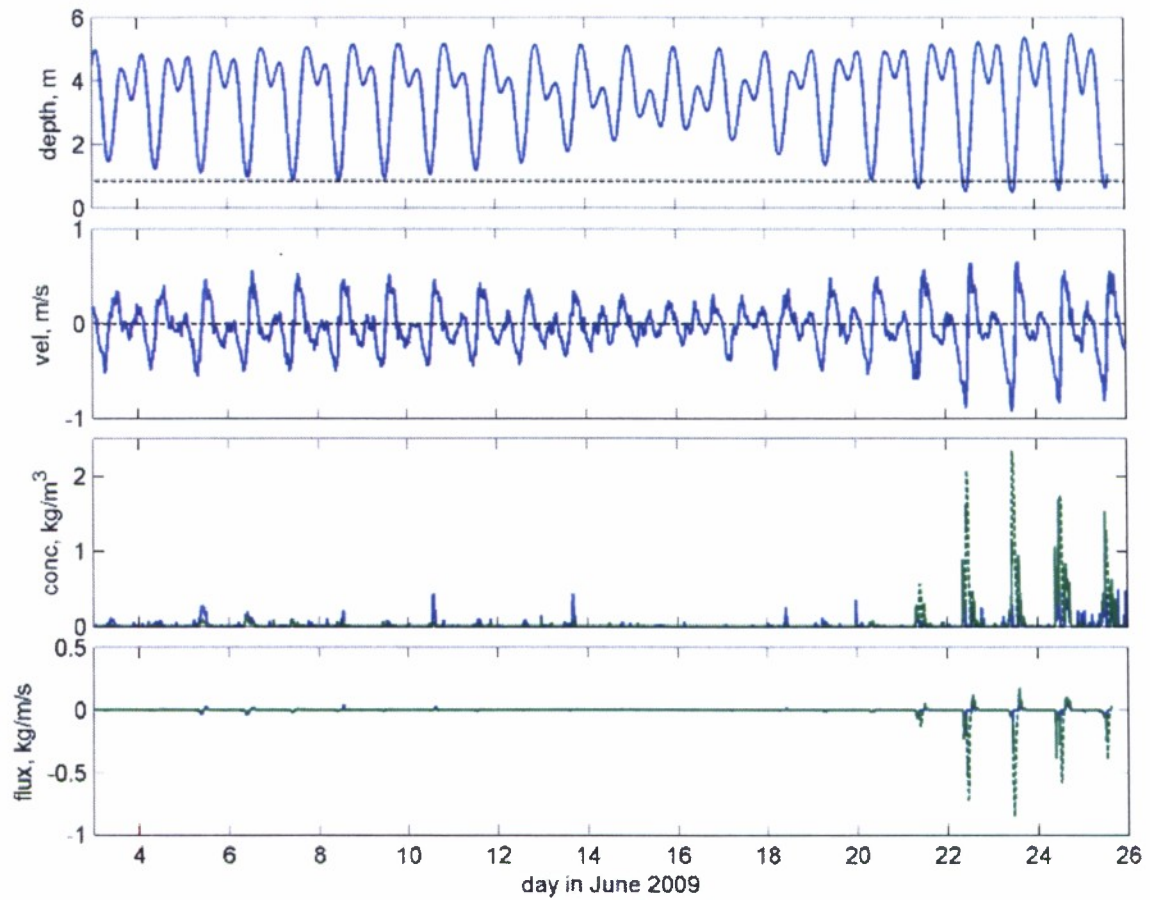


***Figure 2. Schematic of quadpods showing a typical equipment configuration. Each quadpod was accompanied by a upward looking acoustics Doppler current profiler (ADCP) and a bottom mounted conductivity/temperature/pressure sensor.***

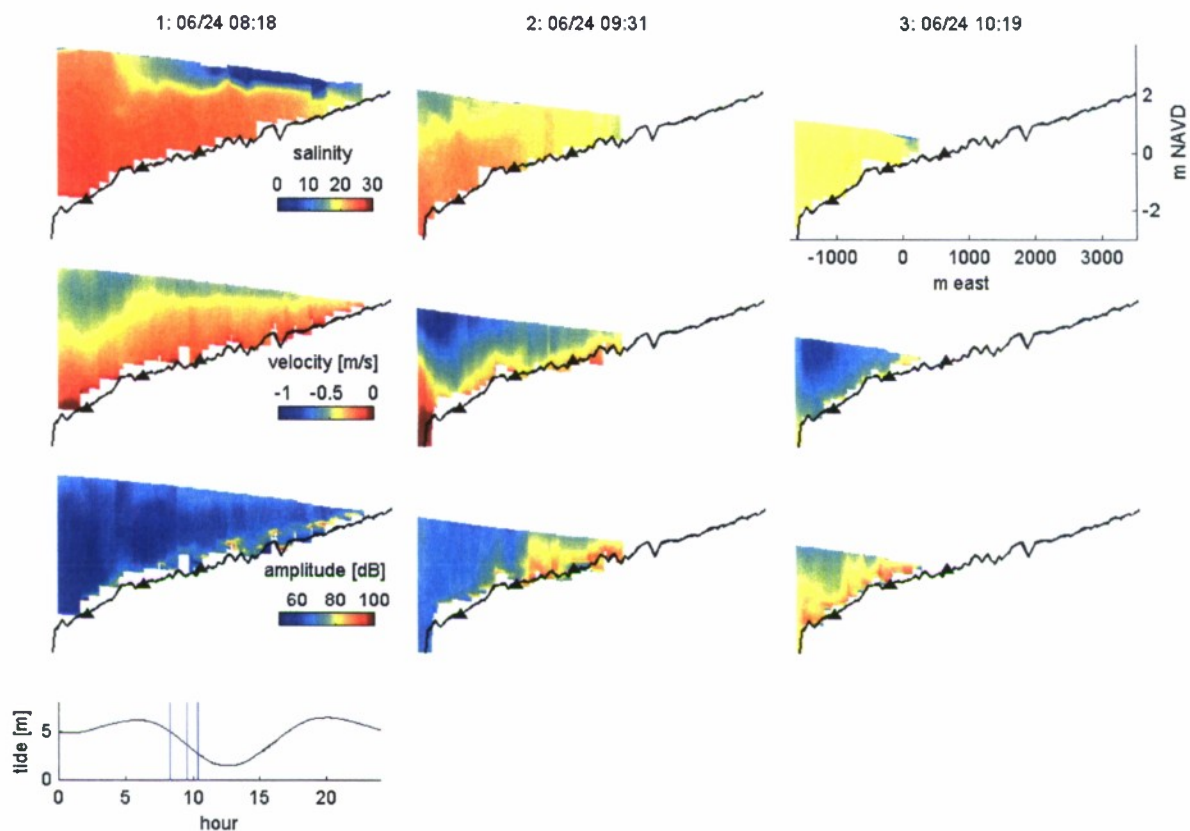




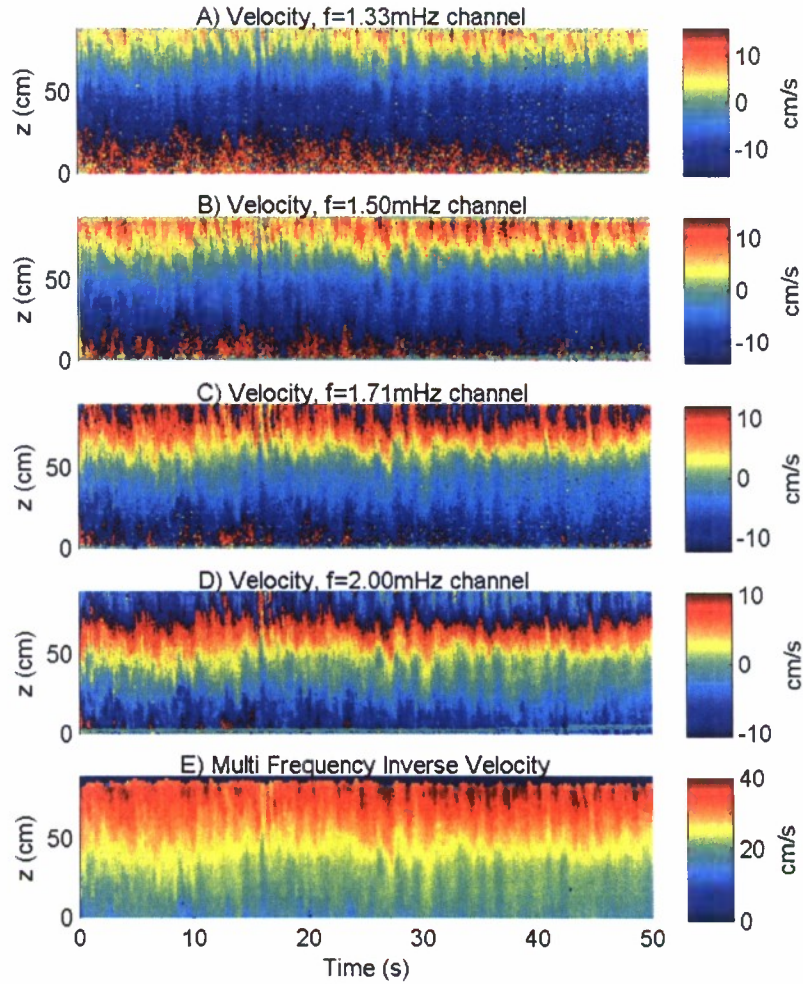
**Figure 3. Time series of river discharge, salinity, along-channel velocity, across-channel velocity, and bottom stress at stations 1 and 5 (location shown in Fig. 1) during the June 2009 deployment.**



**Figure 4. Time series of elevation, near-bottom velocity , estimated concentration (from acoustic backscatter data), and vertically integrated sediment flux at Station 2) during the June 2009 deployment.**

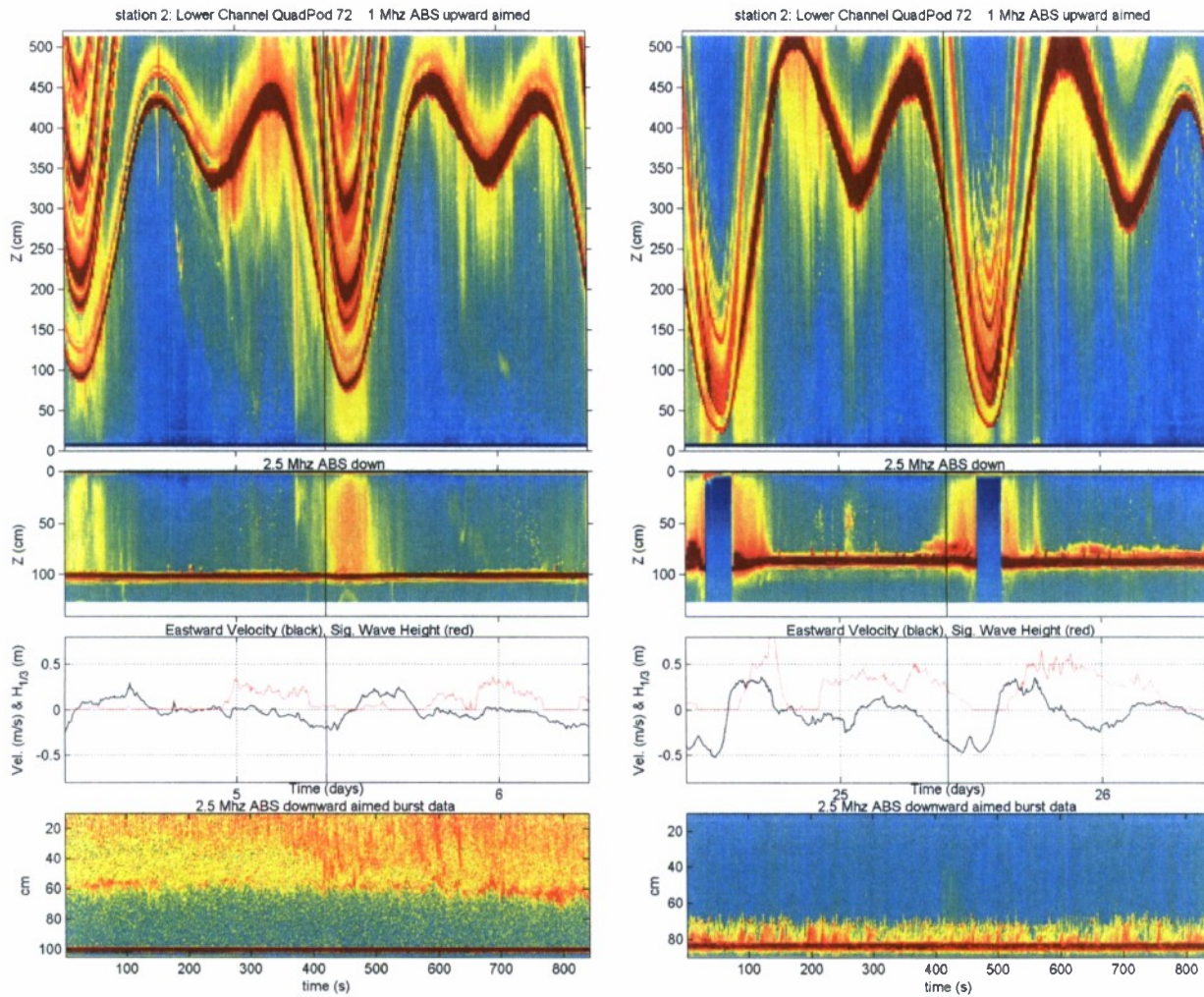


*Figure 5. Three across-flats surveys of salinity (top), velocity (middle), and acoustic backscatter (bottom) during a spring ebb tide on June 24. Tidal elevation is shown in the lower left with the survey times indicated; positions of stations 1, 2, and 5 are marked with triangles on the transects. The sloping water surface reflects the change in water elevation during each transect.*



**Figure 6. Multi-frequency pulse coherent Doppler data. Panels A through D show data from the individual frequencies (1.33, 1.50, 1.71, and 2.0 mHz) of the multi-frequency system. Velocity aliasing at 10 to 16 cm/s, depending on the frequency, can be clearly seen in all the individual channels. The aliasing seen near 80 cm above the bed in the 2.0 mHz data (E) is in fact a double wrap. The only non-aliased data in the individual frequencies is near the bed on the 1.33 (A) and 1.5 (B) mHz channels. The multi frequency inverse solution (E) is able to de-alias the data and produce high resolution data with along beam velocities of 10 to 40 cm/s ( $\sim 1$  m/s horizontal flow).**





**Figure 7.** ABS data taken during ebb tide on March 5<sup>th</sup> (at the beginning of the deployment with high river discharge; left panels), and on March 5<sup>th</sup> (End of the deployment during lower river discharge, larger tides, and larger waves; right panels). The upper plots show two days of 1 mHz upward aimed burst averaged data showing acoustic reflections from the water surface and scattering from fine sediment and turbulent microstructure in the upper water column. The 2<sup>nd</sup> row of plots shows 2.5 mHz downward aimed burst averaged data, and the 3<sup>rd</sup> row shows eastward velocity from an Nortek Vector ADV and significant wave height. The bottom row of plots show an individual burst (840 seconds of data) taken at the time indicated by the vertical black line in the other plots. In the left bottom panel, salinity stratification located 40 cmab prevents the high scattering water associated with the river plume from reaching the bed, and there is little sediment resuspended off the bed. In contrast, during more energetic conditions, shown on the right, near bed stratification contains the suspension in a near bed layer within 10 cm of the bed.